

## ASSOCIATED TOP-HIGGS PRODUCTION AT FUTURE COLLIDERS

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We discuss the relevance of the associated production of a Higgs boson with a pair of top-antitop quarks at both the LHC and a future high energy  $e^+e^-$  collider.

### 1. Overview and motivations

The present and next generation of colliders will help elucidating the nature of the electroweak symmetry breaking and the origin of fermion masses. Lower bounds on the Higgs mass have been placed by LEP II:  $M_{h_{SM}} > 113.2$  GeV for the Standard Model (SM) Higgs, and  $M_{h^0, A^0} > 90.5$  GeV for the light scalar and pseudoscalar SUSY Higgs<sup>1</sup>. At the same time, precision fits of the Standard Model seem to indirectly point at the existence of a light Higgs boson ( $M_{h_{SM}} < 170 - 210$  GeV)<sup>1</sup>, while the Minimal Supersymmetric Standard Model (MSSM) requires the existence of a scalar Higgs lighter than about 130 GeV. Therefore, the possibility of a Higgs discovery in the mass range around 120 – 130 GeV seems around the corner. If this does not happen by the Run II of the Tevatron, and if the Higgs mechanism is the way the electroweak symmetry is broken, almost certainly the LHC will discover it.

In this context the production of a Higgs boson (both SM and MSSM) in association with a pair of top-antitop quarks is of extreme interest for two reasons. First, the  $t\bar{t}H$  production mode can be important for discovery of a Higgs boson around 120 – 130 GeV at the LHC<sup>2</sup>, and even at the Run II of the Tevatron with high enough luminosity, as recently suggested<sup>3</sup>. Second, this production mode offers a direct handle on the Yukawa coupling of the top quark, supposedly the most relevant one to understand the nature of fermion masses. The Run II of the Tevatron will not have enough statistics to use this feature, but both the LHC and in particular a future high energy  $e^+e^-$  collider will be able to try a precision measurement of the  $t\bar{t}H$  coupling.

In view of the role that this production mode can play in discovering and studying the nature of a Higgs boson, we need to improve its theoretical prediction and start developing more and more realistic simulations. In particular it becomes cru-

cial to estimate the feasibility of a precision measurement of the  $t\bar{t}H$  coupling at the LHC and to compare it with the reach of a high energy  $e^+e^-$  collider.

## 2. Associated top-Higgs production at a high energy $e^+e^-$ collider

The process  $e^+e^- \rightarrow t\bar{t}H$  has been studied quite extensively in the last couple of years. The cross section turns out to be highly sensitive to the top Yukawa coupling, both in the SM and in the MSSM, over most of the parameter space. It has been calculated both in the SM and in the MSSM at  $O(\alpha_s)^{4,5}$ . The main source of theoretical uncertainty remains the scale dependence in  $\alpha_s(\mu)$ , which is however below 10%. For a SM Higgs, the factor  $K = \sigma_{NLO}/\sigma_{LO}$  at  $\sqrt{s} = 500$  GeV is in the range (1.4 – 2.4), depending on  $M_H$ . However the cross section is drastically suppressed by phase space and for  $M_H \simeq 120 - 130$  GeV is of the order of 0.1 fb. On the other hand, at  $\sqrt{s} = 1$  TeV the cross section for  $M_H = 120 - 130$  GeV is about 2 fb and is only slightly reduced by QCD corrections ( $K = 0.8 - 0.9$ ). Similar results holds in the MSSM case, where the main channels are the scalar ones, i.e.  $t\bar{t}h^0$  and  $t\bar{t}H^0$ , since the pseudoscalar mode  $t\bar{t}A^0$  is very suppressed over most of the MSSM parameter space. Both the SM and the MSSM results are illustrated in Figure 1.

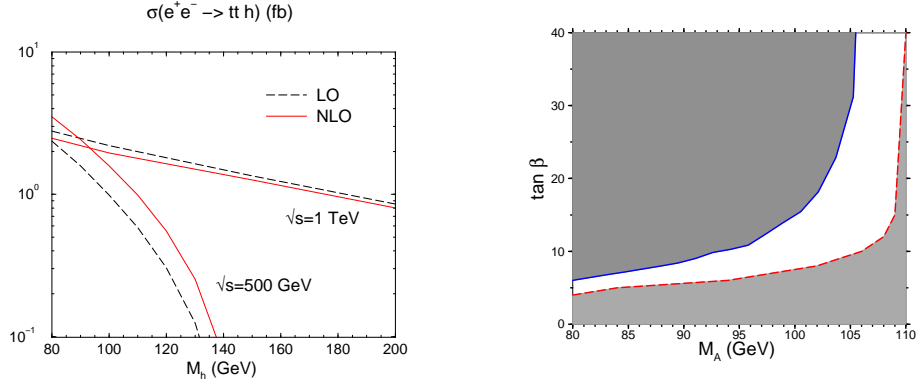


Figure 1: *Left plot:* the  $O(\alpha_s)$  QCD cross section is compared to the lowest order cross section. In both cases, curves are shown for both  $\sqrt{s} = 500$  GeV and  $\sqrt{s} = 1$  TeV. *Right plot:* Regions in the  $M_A - \tan\beta$  plane where the cross section for  $e^+e^- \rightarrow t\bar{t}h_i^0$ , ( $h_i^0 = h^0, H^0$ ), production is larger than 0.75 fb at  $\sqrt{s} = 500$  GeV. The upper left hand region results from  $e^+e^- \rightarrow t\bar{t}H^0$ , while the region at the lower right is the result from  $e^+e^- \rightarrow t\bar{t}h^0$ . All NLO QCD corrections are included. The squarks are taken to have a common mass,  $M_S = 500$  GeV and we assume no-mixing.

Although the cross section is very small, the signature for  $t\bar{t}H$  production is spectacular. The possibility of fully reconstructing the two top quarks in the final state allows to better discriminate the signal over the background, and, together with a good b-tagging efficiency, is crucial in increasing the precision with which

the top Yukawa couplings ( $g_{ttH}$ ) can be measured at a high energy  $e^+e^-$  collider. A first qualitative analysis<sup>6</sup> for a Standard Model Higgs boson has indicated that it will be very hard to get a precise measurement at  $\sqrt{s}=500$  GeV, even at high luminosity, given the very limited statistics. However precisions of the order of 7–15% (statistical error only) are reachable at  $\sqrt{s}=1$  TeV for  $M_H$  around 120-130 GeV (and  $H \rightarrow b\bar{b}$ ), assuming a b-tagging efficiency between 0.6 and 1.

It is interesting to observe that the optimal center of mass energy for this process is neither  $\sqrt{s}=500$  GeV nor  $\sqrt{s}=1$  TeV, but some scale in between. Here the impact of QCD corrections is mild as for the  $\sqrt{s}=1$  TeV case. A detailed simulation<sup>7</sup> of  $e^+e^- \rightarrow t\bar{t}H$  for a SM Higgs, at  $\sqrt{s}=800$  GeV, has found that the top Yukawa coupling can be measured with a precision of 5.5%, when optimal b-tagging efficiency is assumed.

### 3. Associated top-Higgs production at the LHC

The cross section for  $p\bar{p} \rightarrow t\bar{t}H$  or  $pp \rightarrow t\bar{t}H$  is currently known only at the tree level<sup>8</sup>, and is therefore affected by a very strong scale dependence, as can be seen in Figure 2 for the case of a SM Higgs. The calculation of the  $O(\alpha_s)$  QCD correction is work in progress by several groups.

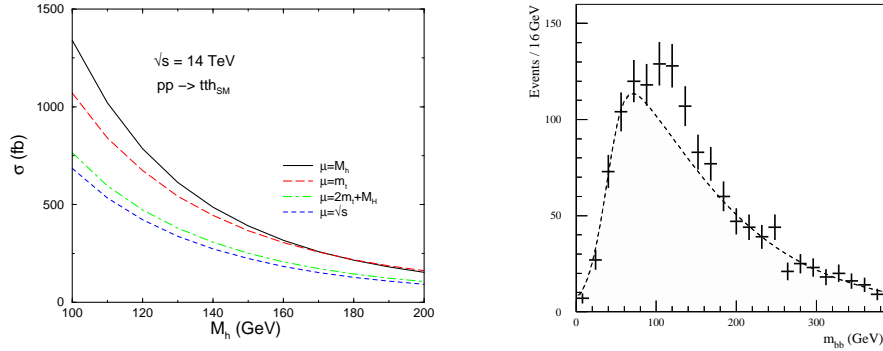


Figure 2: *Left plot*: Cross section for  $t\bar{t}h_{SM}$  production at the LHC ( $\sqrt{s}=14$  TeV) as a function of the Higgs mass, for several values of the scale  $\mu$ . *Right plot*: Invariant mass distribution of tagged  $b$ -jet pairs in fully reconstructed  $t\bar{t}h_{SM}$  signal events and background events, obtained using the fast simulation of the ATLAS detector, for  $m_{h_{SM}}=120$  GeV and integrated luminosity of  $100\text{ fb}^{-1}$  ( $30\text{ fb}^{-1}$  for low luminosity and  $70\text{ fb}^{-1}$  for high). The points with error bars represent the result of a single experiment and the dashed line represents the background distribution.

The existing analyses have been performed for a Standard Model like Higgs and have assumed a small theoretical uncertainty, as we expect to be the case by the time both the Run II of the Tevatron and the LHC turn on. The relevance of the  $t\bar{t}H$  channel for Higgs discovery at the Tevatron has been discussed in a parallel session of this meeting<sup>3</sup>. For the LHC, most of the analyses have been performed by the ATLAS collaboration<sup>9,10</sup> and have been recently summarized in

the context of an LHC workshop<sup>11</sup>, to which we refer for full details. It has been shown that, within the Standard Model,  $t\bar{t}H$  ( $H \rightarrow b\bar{b}$ ) is among the most important channels for discovery of a low mass Higgs ( $M_H \simeq 100 - 130$  GeV). In this channel it is possible to obtain a quite large signal significance and also to measure the top Yukawa coupling. An example of the signal that can be obtained in the invariant  $b\bar{b}$  mass distribution for  $100\text{ fb}^{-1}$  of integrated luminosity is shown in Figure 2. For the same set of parameters and integrated luminosity, and assuming a separate determination of the  $b\bar{b}H$  Yukawa coupling, the top Yukawa coupling can be determined with a precision of about 16%. Further analyses which include more Higgs decay channels will very likely improve this precision.

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